Decay analysis of compound nuclei formed in reactions with exotic neutron-rich $^9$Li projectile and the synthesis of $^{217}$At* within the dynamical cluster-decay model

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Abstract

The decay of various compound nuclei formed via exotic neutron-rich $^9$Li projectile is studied within the dynamical cluster-decay model (DCM). Following the earlier work of one of us (RKG) and collaborators (M. Kaur et al. (2015) [1]), for an empirically fixed neck-length parameter $\Delta R_{\text{emp}}$, the only parameter in the DCM, at a given incident laboratory energy $E_{\text{Lab}}$, we are able to fit almost exactly the (total) fusion cross section $\sigma_{\text{fus}} = \sum_{X=1}^{6} \sigma_{xn}$ for $^9$Li projectile on $^{208}$Pb and other targets, with $\sigma_{\text{fus}}$ depending strongly on the target mass of the most abundant isotope and its (magic) shell structure. This result shows the predictable nature of the DCM. The neck-length parameter $\Delta R_{\text{emp}}$ is fixed empirically for the decay of $^{217}$At* formed in $^9$Li + $^{208}$Pb reaction at a fixed laboratory energy $E_{\text{Lab}}$, and then the total fusion cross section $\sigma_{\text{fus}}$ calculated for all other reactions using $^9$Li as a projectile on different targets. Apparently, this procedure could be used to predict $\sigma_{\text{fus}}$ for $^9$Li-induced reactions where experimental data are not available. Furthermore, optimum choice of “cold” target-projectile combinations, forming “hot” compact configurations, are predicted for the synthesis of compound nucleus $^{217}$At* with $^8$Li + $^{208}$Pb as one of the target-projectile combination, or another ($t$, $p$) combination $^{48}$Ca + $^{169}$Tb, with a doubly magic $^{48}$Ca, as the best possibility.

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1. Introduction

Heavy ion reactions involving weakly or loosely bound projectiles, including halo-nuclei, are of great interest these days because their low break-up threshold profoundly affects the fusion process and thus pose new challenges, both for theory and experiments. In a recent work of Gupta and collaborators [1], it is shown that, within the dynamical cluster-decay model (DCM) [2,3], the (total) fusion cross section \( \sigma_{\text{ fus}} \) \( (= \sum_{x=1}^{6} \sigma_{xn}) \) can be obtained quite accurately as the pure compound nucleus (CN) formation/decay process at a fixed neck-length \( \Delta R^{\text{emp}} \), the only parameter of the model, for various reactions formed with the same weakly bound projectile on different targets, at a chosen incident laboratory energy \( E_{\text{ Lab}} \). The reactions considered in this study [1] are with neutron-rich \(^7\text{Li}\) and \(^9\text{Be}\), and neutron-deficient \(^7\text{Be}\) projectiles on various targets forming compound nuclei in the mass region \( A_{\text{ CN}} \sim 30–200 \). Interestingly, in a more recent work [4], the same result of total \( \sigma_{\text{ fus}} \) being a pure compound nucleus (CN) decay cross section at a fixed neck-length \( \Delta R^{\text{emp}} \) is obtained for \(^9\text{Li} + ^{208}\text{Pb} \) reaction at each incident \( E_{\text{ Lab}} \) or center-of-mass energy \( E_{\text{c.m.}} \). However, it is shown that, if the individual contributing decay channel cross sections \( \sigma_{xn} \), \( x = 1–6 \), were also fitted, then, instead of the large expected pure CN cross section due to the doubly magic \(^{208}\text{Pb} \) target, \( \sigma_{\text{ fus}} \) is mainly of the non-compound nucleus (nCN) content. Hence, it is of great interest to look for other possible targets to be used with \(^9\text{Li} \) beam, which we do in this paper. In other words, we extend our earlier study [1] to another equally exotic neutron-rich \(^9\text{Li} \) projectile on various different targets. It is relevant to remind here that, in DCM, the dynamical collective mass motion of preformed light-particles (LPs, \( A \leq 4 \), referred to as the evaporation residues ER), energetically favored intermediate mass fragments (IMFs, \( 5 \leq A_2 \leq 20 \)) and fusion–fission \( ff \) fragments or clusters, through the ‘modified’ interaction barriers, are treated on the same footing, where the modification of the barrier is introduced via empirical neck-length parameters \( \Delta R^{\text{emp}} \)'s, with corresponding modified barrier heights \( \Delta V_{B}^{\text{emp}} \) for such reactions being almost of the same order at the, respective, \( \ell_{\text{ min}} \) or \( \ell_{\text{ max}} \) value [1].

\(^9\text{Li} \) projectile, used in present study, is a very neutron-rich \((N = 2Z) \) nucleus, with a significant amount of neutron skin \((= 0.48 \text{ fm in a neutron radius of } 2.59 \text{ fm} [5]) \), whose fusion excitation function at near- and sub-barrier energies are measured for only two neutron-rich \(^{70}\text{Zn} \) [6] and \(^{208}\text{Pb} \) [7] target nuclei. Earlier experimental studies of the use of \(^9\text{Li} \) projectile were made at intermediate energies \((80 \text{ MeV/nucleon}) \), namely of the elastic scattering of \(^9\text{Li} \) [8] and total interaction cross section of \(^9\text{Li} \) on intermediate mass targets, such as \( \text{C, Al, Cu, Sn and Pb} \) [9]. Also, the fusion of \(^9\text{Li} \) with \( \text{Si} \) at \( 11.2\text{A}–15.2\text{A MeV} \), and at a projectile energy of \( 36 \text{ MeV} \) with \(^{209}\text{Bi} \) were studied at RIKEN \([10,11]\), measuring the evaporation residues and any associated neutrons, but no fusion cross sections were measured. In the present paper, we analyze some of these \(^9\text{Li} \) based reactions at near- and above-barrier energies. Note that in most of the above noted reactions at intermediate energies, the isotopic mass of the target is not known, which is one of the endeavor of our present study at low energies.

Since \(^9\text{Li} \) is known to be the core of \(2n\)-halo nucleus \(^{11}\text{Li} \), it is believed \([7,12]\) that studying the reactions with \(^9\text{Li} \) as a projectile will help us understand the interactions with other neutron-rich nuclei, like \(^{11}\text{Li} \) itself. Apparently, break-up effects could play a significant role on the fusion of halo-nucleus \(^{11}\text{Li} \), as is explicitly shown, for example, by Takigawa et al. \([13]\) by incorporating the effects of breakup via a local dynamic polarization potential, or measured as incomplete fusion (ICF) cross section in capture of one of the breakup fragment of projectile by the target in \(^6\text{Li} + ^{238}\text{U} \) reaction [14], which is recently understood within the DCM [15] as an ICF process for the break-up of \(^6\text{Li} \) in to \( \alpha + d \) at relatively higher energies, with \( \alpha \) taken [16] to interact strongly...
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